

# Combustion Dynamics of Swirling Flame at Thermochemical Conversion of Biomass

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Development of the swirling flame dynamics at thermo chemical conversion of biomass (wood pellets) has been investigated experimentally at a low swirl number of the swirling flame flow ( $S < 0.6$ ), different rates of biomass thermal decomposition and swirling air supply with the aim to estimate key factors determining the formation of the flame dynamics and local variations of the flame temperature, composition and processes of heat energy production for such type of swirling flame flow. The experimental study is carried out using a small-scale pilot device with an integrated wood biomass gasifier and combustor. The limited primary axial air supply below the layer of wood pellets ( $\alpha < 0.5$ ) is used to support biomass gasification, and the secondary swirling air at air excess supply ( $\alpha > 1$ ) is used to provide mixing of the axial flow of volatiles with an air swirl and to support the combustion of volatiles with the formation of a downstream reaction zone. It is shown that the development of combustion dynamics is influenced by the competitive processes of endothermic thermal decomposition of biomass and exothermal combustion of volatiles. The enhanced thermal decomposition of biomass by increasing the primary air supply and the axial flow of volatiles results in an intensive heat energy consumption with a correlating increase of the air excess ratio at the bottom of the combustor and in ignition delay. This determines the incomplete combustion of the volatiles at the primary stage of flame formation and restricts the development of combustion dynamics. The combustion conditions can be improved by decreasing the secondary air supply and air excess ratio at the bottom of the combustor, which leads to enhanced ignition with a faster and more complete combustion of volatiles.

## 1. Introduction

Biomass is now gaining in importance as a renewable source (Klass, 2004) for cleaner heat and power production (Barmina et al, 2013) by minimizing the impact of energy production on the Earth's climate changes (Nussbaumer, 2008). The availability of cheap renewable energy resources (forestry and agriculture residues, herbaceous biomass, etc.) combined with the effective technologies of thermo chemical conversion of biomass and low polluting emission makes them an attractive fuel for energy production. At the same time, the utilization of biomass for controllable and stable energy production faces some problems related to the thermal decomposition of biomass and combustion of produced volatiles that requires knowledge of methods for control and stabilization of combustion dynamics. Previous research has shown that effective stabilization (Driscoll et al, 2011), control of the flame dynamics (Vondal et al, 2012) and combustion characteristics can be achieved under conditions of swirl-enhanced mixing of the flame components (Gupta et al, 1984) determining a cleaner and more effective fuel combustion that is highly influenced by swirl intensity (Candel et al, 2012) depending on the swirl number ( $S$ ) of the inlet flow (Abricka et al, 2014). With a high swirl intensity ( $S > 0.6$ ), the swirl-enhanced recirculation along with the swirl-enhanced mixing of fuel with the air leads to enhanced heating, ignition and combustion of fuel components, whereas the development of combustion instability (Stöhr et al, 2009) with a flame flashback can occur (Fritz et al, 2001). An alternative approach to flame stabilization is the use of low swirl burners (Chen, 2008) by operating at a low swirl intensity ( $S < 0.6$ ) below the vortex breakdown threshold and producing a non-recirculating flow characterized by flow divergence, with linear decay of the axial velocity in the flame downstream regions and by the formation of clean and complete

combustion of gaseous fuel ( $\text{CH}_4$ ) with low  $\text{NO}_x$  and CO emissions (Cheng, 1995). Accordingly, with the aim to improve the combustion dynamics and composition of emission at the thermo chemical conversion of batch-size biomass pellets, an experimental study on the formation of combustion dynamics and flame structure is carried out at a low swirl intensity ( $S < 0.6$ ), with estimation of the flame response to the variations of the relation between the axial flow of volatiles and the air swirl, determining variations of the swirl intensity, mixing of the flame components, the formation of flame dynamics, flame structure, and combustion characteristics.

## 2. Experimental

The experimental setup (Figure 1) has been designed to provide a controllable process of thermo chemical conversion of pelletized renewable fuel (wood pellets) for the integrated processes of biomass gasification and combustion of volatiles produced at thermal decomposition of biomass.

The experimental setup consist of a gasifier (1) charged with biomass pellets (240 g), water-cooled sections of the combustor (3) with the inner diameter  $D = 60$  mm and a total length of  $L = 700$  mm and diagnostic sections (4) with orifices for diagnostic tools. The propane burner (2) is used as an external heat source with an average heat power 1-1.2 kW to initiate thermal decomposition (gasification) of biomass, as well as ignition and combustion of volatiles at the primary stage of flame formation, and it is switched out after the ignition of volatiles. The primary air was supplied below the biomass layer to support the biomass gasification and initiate the formation of the axial flow of volatiles ( $\text{CO}$ ,  $\text{H}_2$ ,  $\text{C}_x\text{H}_y$ ). The primary air was supplied below the biomass layer at the limited average air supply rate ranging from  $q_{\text{air}1} = 0.38$  g/s to  $q_{\text{air}1} = 0.64$  g/s, determining the variations of the air excess ratio ranging from  $\alpha \approx 0.25$  to  $\alpha \approx 0.5$ . The secondary swirling air at the average rate  $q_{\text{air}2} = 0.64 - 0.9$  g/s was supplied above the biomass layer through two tangential nozzles to provide the mixing of the axial fuel flow with the air and support the combustion of volatiles under lean pre-mixed combustion conditions downstream the combustor with the average air excess ratio  $\alpha \approx 1.5 - 2$ . The effect of the primary and secondary air supply rates on the process of thermo chemical conversion of biomass pellets at a low swirl intensity ( $S < 0.6$ ) were experimentally studied and analyzed by varying the ratio between the primary and secondary air supply rates, with estimation of the flame response to the variations of the mass flow rate of the volatiles and air on the combustion dynamics and on the flame structure formation.

In order to estimate the weight loss of biomass pellets during their thermal decomposition, the time-dependent variations of the batch-size biomass height are measured using a moving rod with pointer and providing measurements of the time-dependent variations of biomass height ( $dL/dt$ , cm/s) with accuracy  $\pm 1$  mm. From measurements of the average value of pellets bulk density in the gasifier ( $0.601 \pm 0.005$  g/cm<sup>3</sup>) the time-dependent variations of the weight loss rate of pellets ( $dm/dt$ , g/s) were estimated.

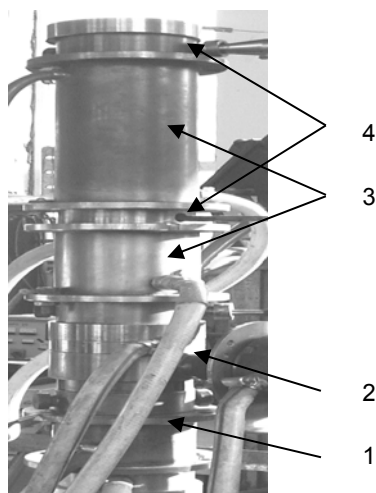


Figure 1: Photograph of the experimental setup.

Local online measurements of the flame temperature are made using a Pt/Pt-Rh thermocouple and recorded using a PC-20TR plate. Local measurements of the flame velocity are made by a Pitot tube and recorded using a Testo 435 flow meter. Local measurements of the products composition are made using a gas sampling probe and recorded using a gas analyzer Testo 350 XL. Spectral measurements of the produced gas at biomass thermal decomposition are made by a gas sampling probe and FTIR spectroscopy. Calorimetric measurements of the cooling water flow of the gasifier and combustor are made to estimate the

released heat power ( $P$ , kW) and produced heat energy ( $Q$ , MJ/kg) at different stages of thermo chemical conversion of wood pellets.

The gasification and combustion characteristics in this study were explored and analyzed for commercial wood pellets with the average moisture content 7.9 %, ash content 2.1 %, carbon content 50.2 %, hydrogen content 5.7 %, nitrogen content 0.18 % and with the lower heating value 4.6 kWh/kg.

### 3. Results and discussion

The biomass thermochemical conversion in the recent study developed as a two-stage process including the primary stage of biomass thermal decomposition determining an intensive release of the combustible volatile compounds ( $\text{CO}$ ,  $\text{H}_2$ ,  $\text{C}_x\text{H}_y$ ) during the primary stage of biomass gasification and the next stage of the volatiles combustion downstream the combustor. The process of biomass thermal decomposition leads to time-dependent variations of the weight loss rate of biomass pellets ( $dm/dt$ , g/s) with correlating variations of the composition of the produced axial flow of the volatiles and absorbance of the produced gas at the bottom of the combustor ( $L/D = 0.6$ ) (Figure 2-a, b).

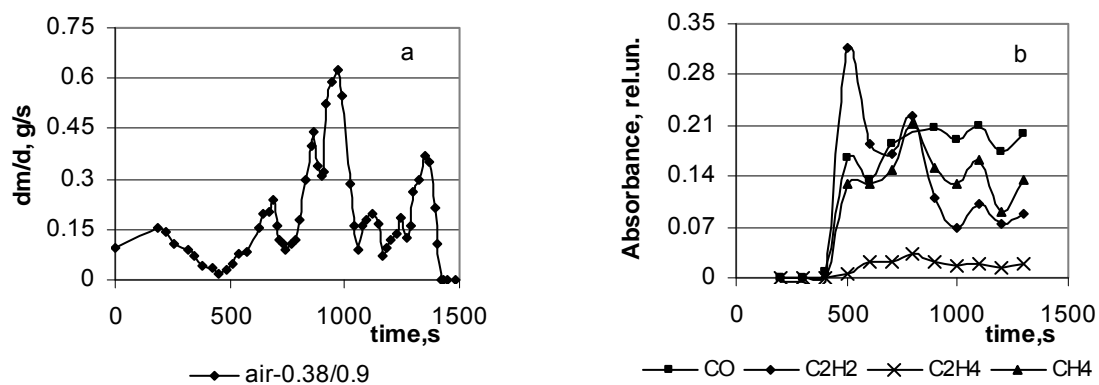


Figure 2: Time-dependent variations of the weight loss of wood pellets' biomass samples (a) at thermal decomposition and absorbance of the produced gas ( $q_{\text{air}1} = 0.38$ ;  $q_{\text{air}2} = 0.9$  g/s) (b)

The average value of biomass weight loss rate was estimated by assessing the full time for the complete thermo chemical conversion of discrete doses of wood pellets (240 g), which were fed into the gasifier. The estimation of time-averaged values of the weight loss rates have shown that increasing of the primary air supply rate ( $q_{\text{air}1}$ , g/s) resulted in a correlating increase of the biomass weight loss rate (Figure 3-a). Moreover, increasing of the primary air supply and biomass weight loss results in an increase of the values of the axial and tangential flow velocities at the bottom of the reaction zone, which were averaged per radius of the reaction zone during the stage, when the burnout of volatiles is developing at nearly constant average temperature (Figure 3-b).

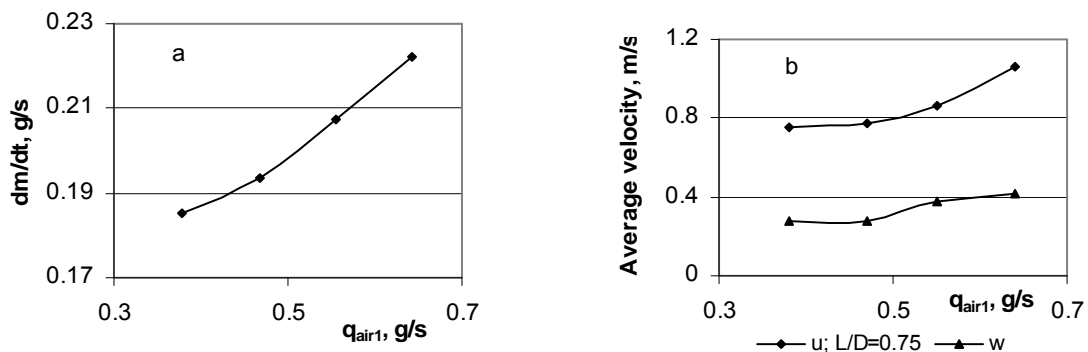


Figure 3: The effect of the primary air supply rate on the weight loss of biomass samples (a) and average values of the axial and tangential flow velocity compounds (b) at the bottom of the reaction zone

The biomass thermal decomposition determining the formation of the axial flow of volatiles and the mixing of volatiles with air swirl is closely related to the development of flow dynamics. In accordance with the results of the previous experimental study and numerical simulation, the formation of swirling flow dynamics (Abricka, 2014) for the given system configuration is strongly influenced by the upstream swirling air flow formation that propagates towards the biomass layer with primary swirl-enhanced mixing of the axial flow of volatiles with the upstream air swirl. The swirl flow reverse from the biomass layer results in the formation of a secondary downstream swirling flow close to the centreline of the device determining the formation of the axial reaction zone with peak values of the axial flow velocity, temperature and volume fraction of the main products close to the flame axis. The development of the downstream axial and tangential flows at the low swirl intensity ( $S < 0.6$ ) indicates that a typical feature of the primary stage of the swirling flame velocity field formation ( $L/D < 0.75$ ), is the primary fast drop of the average value of the axial flow velocity and average flame temperature to the minimum value (Figure 4-b). The axial and swirling air downstream flows at this stage of the flame formation are spatially separated (Figure 4a,d) and the endothermic processes of the thermal decomposition of biomass components dominate (Figure 2b). At the next stage of the swirling flow formation ( $L/D > 0.75$ ), when the intensive mixing of the axial and swirling air downstream flows is followed by the ignition and combustion of the volatiles with radial expansion of the reaction zone (Figure 4a), the average values of the axial and swirling air downstream flow velocities and temperature increase up to their peak values and then start to decrease determining the formation of the diverging flow field with the correlating decrease of the axial and tangential flow velocities and average flame temperature (Figure 4b), as it is observed for the diverging flows of low swirl intensity (Cheng, 1995) (Figure 4a,b). The shape of the flow velocity profiles is influenced by the variations of the primary and secondary air supply at the bottom of the reaction zone. The measurements of the flame velocity profiles at a nearly constant secondary air supply and low swirl intensity ( $S = 0.25$ ) showed that the increase of the primary air supply, as well as the enhancing of the biomass thermal decomposition and mixing of volatiles with the upstream swirling airflow results in a correlating increase of the axial velocity over the entire central part of the flow field  $r/R < 0.7$  (Figure 4c). A pronounced deformation of the flow velocity profiles along the airside part of the reaction zone ( $r/R > 0.5$ ) was observed when increasing the secondary air supply and the downstream air swirl intensity from  $S = 0.25$  to  $S = 0.32$ , which was a result of the swirl enhanced mixing of the downstream axial flow with the swirling air flow along the airside part of the reaction zone (Figure 4d).

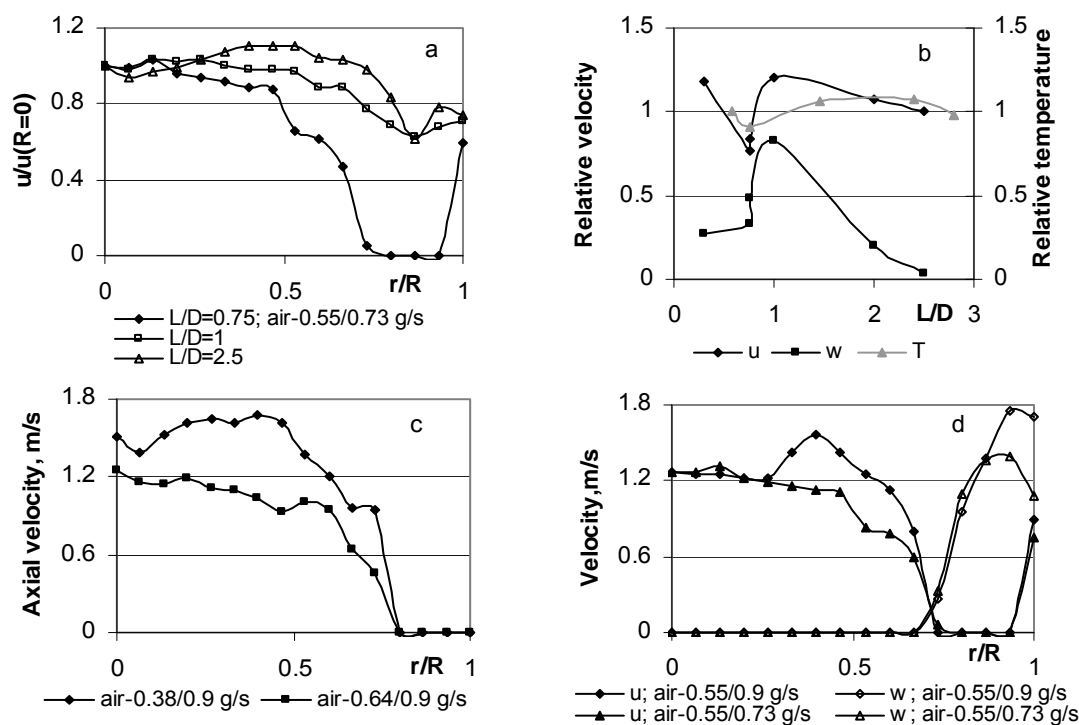


Figure 4: The effect of primary and secondary air supply rates on the formation of radial velocity profiles at different stages of swirling flame formation (a,c,d); the formation of downstream velocity and temperature profiles (b).

The increase of the primary air supply into the biomass layer and the enhancing of the biomass thermal decomposition along with the development of the endothermic processes of hydrocarbons thermal decomposition at the primary stage of flame formation give evidence of the direct impact on the formation of the main combustion characteristics and on the time-dependent variations of the flame temperature, composition and released heat power at different stages of biomass thermo chemical conversion. The complex measurements of the time-dependent variation of the main combustion characteristics have revealed that the enhanced thermal decomposition of biomass and the development of the endothermic processes at the primary stage of the swirling flame formation ( $t < 500$  s) result in a pronounced decrease of the flame temperature, released heat power and  $\text{CO}_2$  volume fraction in the products with the correlating increase of the air excess in the products (Figure 5, a-c).

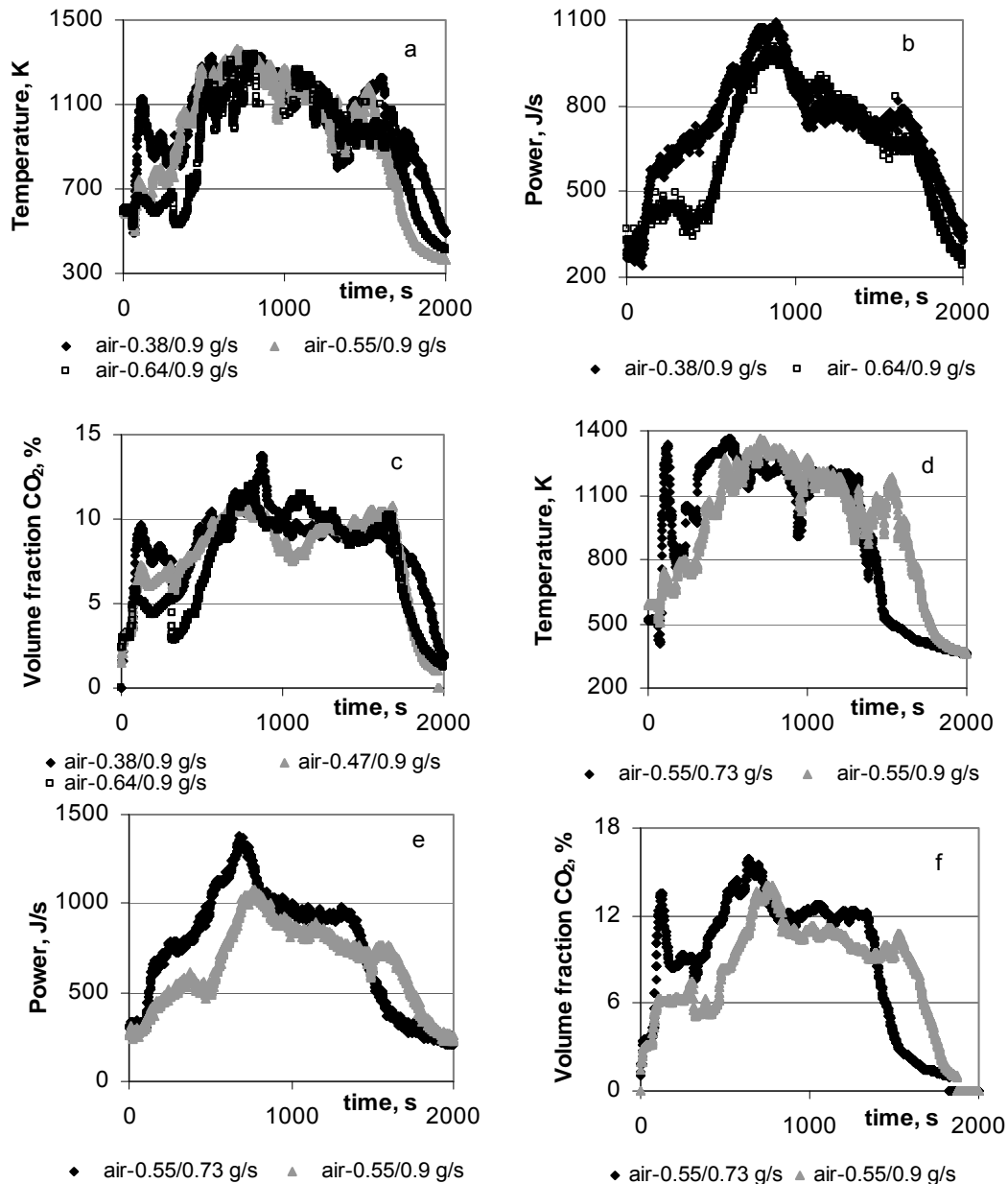


Figure 5: The effect of primary and secondary air supply on the time-dependent variations of the main combustion characteristics at thermo-chemical conversion of biomass.

The above-said confirms that the enhanced development of the endothermic processes of biomass thermal decomposition results in an intensive heat energy consumption from the external heat energy source, which can lead to ignition delay and flame extinction. The kinetic study of the combustion characteristics at different rates of secondary air supply has shown that the combustion conditions at the primary stage of swirling flame formation can be improved by decreasing the secondary swirling air supply and the air excess at the bottom of the reaction zone that leads to a stronger ignition and faster burnout of the volatiles with the correlating increase of the flame temperature, released heat power and volume fraction of CO<sub>2</sub> in the products, with stabilization of the combustion dynamics development (Figure 5, d-f). Moreover, the local measurements of the flame composition show that the formation of the diverging flow with the low swirl intensity ( $S = 0.25 - 0.32$ ) with the gradually decreasing average temperature downstream the flame reaction zone ( $T_{av} < 1,300$  K) and lean combustion conditions ( $\alpha \approx 1.6 - 1.9$ ) advances the clean and complete combustion of the volatiles with the low average values of NO<sub>x</sub> (<70 ppm) and CO emissions (<40 ppm) in the products. Hence, the low swirl diverging flows can be used to minimize the impact of polluting emissions on the surrounding.

#### 4. Conclusions

Based on the results obtained the following conclusions can be drawn.

The thermochemical conversion of biomass pellets develops as a multistage process, which includes the primary stage of endothermic thermal decomposition of biomass developing in the gasifier and the stage of exothermic combustion of volatiles downstream the combustor.

The enhanced thermal decomposition of biomass with the enhanced formation of volatiles results in an intensive heat energy consumption at the primary stage of flame formation with ignition delay that can lead to flame extinction. The combustion characteristics can be improved and the combustion dynamics can be stabilized by balancing the primary and secondary air supply rates that must be optimized to provide a faster ignition with a cleaner and more complete combustion of the volatiles.

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